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Robert M. Hall
NASA Langley Research Center
Hampton, VA

Shawn H. Woodson
Naval Air Systems Command
Patuxent River, MD

Joseph R. Chambers
Ball Aerospace Systems Division
Fairborn, OH

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ACCOMPLISHMENTS OF THE ABRUPT WING STALL (AWS) PROGRAM AND FUTURE RESEARCH REQUIREMENTS

Robert M. Hall*
NASA Langley Research Center
Hampton, VA

Shawn H. Woodson†
Naval Air Systems Command
Patuxent River, MD

Joseph R. Chambers††
Ball Aerospace Systems Division
Fairborn, OH

ABSTRACT

The Abrupt Wing Stall (AWS) Program has addressed the problem of uncommanded lateral motions, such as wing drop and wing rock, at transonic speeds. The genesis of this Program was the experience of the F/A-18E/F Program in the late 1990's, when wing drop was discovered in the heart of the maneuver envelope for the pre-production aircraft. While the F/A-18E/F problem was subsequently corrected by a leading-edge flap scheduling change and the addition of a porous door to the wing fold fairing, the AWS Program was initiated as a national response to the lack of technology readiness available at the time of the F/A-18E/F Development Program. The AWS Program objectives were to define causal factors for the F/A-18E/F experience, to gain insights into the flow physics associated with wing drop, and to develop methods and analytical tools so that future programs could identify this type of problem before going to flight test. The paper reviews, for the major goals of the AWS Program, the status of the technology before the program began, the program objectives, accomplishments, and impacts. Lessons learned are presented for the benefit of future programs that must assess whether a vehicle will have uncommanded lateral motions before going to flight test. Finally, recommended future research needs are presented in light of the AWS Program experience.

SYMBOLS AND ABBREVIATIONS

AWS	abrupt wing stall
c_l	sectional lift coefficient
FOM	figure of merit
FTR	free-to-roll
M_∞	Mach number
PSP	Pressure Sensitive Paint
RMS	root mean square
α	angle of attack, deg
16-ft TT	16-Foot Transonic Tunnel

INTRODUCTION

The Abrupt Wing Stall (AWS) Program has addressed the problem of uncommanded lateral motions, such as wing drop and wing rock, at transonic speeds with experimental, computational, and simulation tools. This coordinated, focused program has been a

*Senior Research Engineer, Associate Fellow, AIAA
† Aerospace Engineer, Associate Fellow, AIAA
††Senior Consultant

cooperative effort of government, industry, and academia.[1] The general objectives of the program are based on the technology shortcomings identified during the wing-drop experience of the pre-production F/A-18E/F aircraft.[2] The AWS Program has extended its research scope beyond the pre-production F/A-18E to include three other aircraft. Further configuration investigations have been conducted with Reynolds-averaged Navier Stokes computational fluid dynamics (CFD) to investigate the specific wing geometric differences between the F/A-18E and the F/A-18C to understand why the pre-production F/A-18E had to overcome the wing drop challenge while the F/A-18C did not. Additional efforts were invested in simulating wing drop with F/A-18E simulation.

The research objectives of the AWS Program can be grouped into 4 major topic areas, see figure 1. The first area of research was to analyze the existing legacy data from the pre-production F/A-18E wing-drop resolution efforts and other historical programs. The F/A-18E wing-drop resolution effort, in particular, offered an abundant source of wind-tunnel data, CFD grids and results, and flight data for the wing-drop events. The second research area included efforts to generate new data to complement and extend the legacy data for the pre-production F/A-18E. This new data addressed the AWS Program objectives of both understanding the flow physics involved in the abrupt stall on the early F/A-18E, as well as establishing a foundation for understanding other configurations. The third research area was that of developing new experimental wind-tunnel methods, figures of merit for wind tunnel and CFD, and improving the mathematical simulation tools. The key objective was to have in place better methods and tools and to advance the state of the art so that a future program can satisfactorily predict whether its aircraft will experience transonic uncommanded lateral motions well before flight tests. The fourth, and last, topic area was to conduct an assessment of the developed methods and figures of merit. This assessment was to be conducted by static and dynamic wind-tunnel test techniques and CFD calculations for two configurations susceptible to wing drop—the pre-production F/A-18E and the AV-8B at extremes of its envelope—and two configurations not susceptible to drop—the F/A-18C and the F-16C.

The paper will summarize the results from each of the four major research areas. The reader is referred to other AWS, or related, reports for a more detailed overview of the research efforts to date.[3-18] Following the highlights of the research areas, lessons learned will be summarized and presented according to discipline—wind tunnel, computations, and simulation. Next, recommendations for future research will also be detailed, based on the AWS Program experience, for two potential efforts. First, it is recommended to conduct additional research to determine generic design guidelines. Second, it is also recommended that an aggressive effort be made to integrate the use of state-of-the-art and emerging CFD methods into the stability and control arena.

In order to obtain approval for releasing this paper to the public, quantitative information has been removed from most vertical scales as directed by guidelines from the Department of Defense.

RESEARCH AREAS

Each major topic area will be organized by subsections, providing the state-of-the-art at the beginning of the AWS Program, efforts undertaken, accomplishments, and impacts.

Legacy Data

State of the Art

At the beginning of the AWS Program, several of the future AWS team members had participated in the pre-production F/A-18E/F wing-drop resolution effort. This background provided an excellent tutorial for what was available from NAVAIR and Boeing efforts in transonic CFD calculations, wind-tunnel efforts, and flight data. By the end of the resolution effort, [1,5] CFD was already pointing to the wing leading-edge snag as a main contributor to the undesirable abrupt stall properties of the F/A-18E wing.

In past generic studies and experiences with other specific aircraft programs, certain flow phenomena had been observed that were believed to contribute to wing drop and wing

rock. Specifically, these phenomena included loss of aerodynamic damping in roll for wings with abrupt stall characteristics, out-of-trim rolling moments at stall, unsteady shock-induced separation at high subsonic and transonic conditions, and dynamic vibrations of models during wind-tunnel tests. Unfortunately, these observations had not been focused into a coordinated effort to develop analysis procedures and figures of merit for the design of future aircraft.

AWS Efforts

The first of two initial contractual efforts funded by the AWS Program was to task Chambers[3] to survey past aircraft programs that experienced uncommanded lateral motions, such as wing drop, wing rock, or heavy wing, at transonic conditions. When the documented occurrences of uncommanded lateral motions were combined, it became clear that many of the high-performance aircraft programs over the past 50 years had experienced problems with lateral motions in the transonic speed regime. In virtually all cases, the degraded lateral behavior had not been predicted prior to actual flight tests in the aircraft development program. The second of the initial contracts was to task Boeing to summarize and organize their broad wind-tunnel efforts to address the F/A-18E/F wing drop studies. In addition, AWS participants, with help from NAVAIR flight-test personnel, were also able to review flight-test information as well as flight videotapes.

Accomplishments

The task by Chambers was important because it clarified the scope and breadth of the challenge that uncommanded lateral motions have been to a variety of aircraft with various leading-edge sweeps, airfoil sections, and other broad differences in planform, see figure 2. Boeing's summary of the legacy F/A-18E data became an invaluable resource for insight into the abrupt stall process for the F/A-18E. It has been particularly useful to the AWS Program in efforts to define the abruptness of the stall process, to define Mach number effects, and for comparison with newer data taken as the AWS Program progressed. Figure 3 details a Boeing-provided example of the abrupt movement of the shock-induced separation from a position significantly aft of the leading-edge flap to a position near the flap hinge line with just a 1° increase in angle of attack to 10°. That the flow was unsteady over the F/A-18E wing in the angle-of-attack range near wing drop became apparent after reviewing the flight videotapes and talking with test flight personnel, see figure 4. This significant observation led to unsteady wind-tunnel measurements and CFD calculations during the course of the AWS Program.

Impact of Results

1. Uncommanded transonic lateral motions, such as wing drop and wing rock, have been documented for a wide variety of aircraft planforms and airfoil sections.[3] In light of this experience, the characteristics of the pre-production F/A-18E/F were not unique by any means. Future high-performance aircraft programs should be alert for the possible existence of this problem beginning early in design and development.

2. Unsteady, shock-induced separation had been observed in past programs; however, the AWS Program focused on unsteadiness as a potentially important aspect of the abrupt stall process.

Developing Flow Understanding

State of the Art

Interpretations of the different aspects of the abrupt-stall process had already surfaced from the legacy pre-production F/A-18E data—wind-tunnel oil flows, CFD solutions, and limited flight information. However, the fundamental abrupt stall process was not understood. For example, was the abruptness of the stall due to leading-edge separation or was it due to the shock-induced, boundary-layer separation migrating forward from the trailing edge? Flow unsteadiness was another issue in some minds.

Another question involved which wing geometry differences between the F/A-18C and the F/A-18E were responsible for the increased sensitivity of the pre-production F/A-18E to wing drop, in contrast to the F/A-18C, which displayed no such problem.

AWS Efforts

Fundamental understanding of physical

phenomena associated with abrupt wing stall was one of the major objectives of the AWS Program. Two major transonic wind-tunnel entries were dedicated to this effort and involved the use and interpretation of steady and unsteady pressure transducers, wing-root bending moments, and Pressure-Sensitive Paint (PSP) images. An equally broad CFD effort was conducted in which three major codes were utilized: WIND[5,14], TetrUSS,[8,9] and COBALT.[7] All three codes were used in the Reynolds-averaged Navier Stokes, time-averaged mode and one code, COBALT, was used in a time-accurate Detached-Eddy Simulation (DES) mode. Both the wind tunnel and CFD efforts were focused on determining the critical flow separation process leading to the abrupt stall. Another very informative study that yielded a large degree of understanding was an effort by Green,[14] who addressed the question of which of the wing geometric differences between the pre-production F/A-18E and the F/A-18C were most responsible for the increased sensitivity to abrupt stall displayed by the pre-production F/A-18E.

Accomplishments

Static and dynamic wind-tunnel results are reported by McMillin,[4] Schuster,[6] Lamar,[10] and Owens.[12] Highlights include the extremely good correlation between force and moment and PSP images as well as PSP and legacy oil flows,[4] see figure 5. Lessons learned included the need to acquire data at small increments in angle of attack (no larger than 0.5°) near wing stall and the importance of testing the model with a sufficient number of different leading-edge flap settings to be able to simulate the aircraft flying on automatic flap schedule through the region of lateral activity. With regard to measurements of flow unsteadiness, Schuster determined from pressure time histories the range of unsteady transonic shock movement and the magnitude of pressure fluctuations as a function of angle of attack. This work also served to provide crucial validation of the unsteady computational work conducted by Forsythe.[7] Additional unsteady information was captured by routing the signals from the wing-root bending gauges, accelerometers, balances, and pressures through RMS (root mean square) instrumentation at the wind-tunnel facility.[4,10,16] These measures of unsteadiness, while not containing any frequency content, produced very valuable insights into the levels of unsteadiness in the flow with very little effort.

The steady-state computational work highlighted the importance of the upwash being generated inboard of the leading-edge snag on the pre-production F/A-18E.[5] This upwash generated by the snag is strongest just inboard of the snag and makes that area along the leading edge most vulnerable to separation. This vulnerability is highlighted by unsteady COBALT DES solutions by Forsythe,[7] see figure 6. His animation of the flow near the notch of the snag illustrated two important observations. First, vorticity is being shed from the snag in the notch region. Second, the amount of vorticity shed and the entire shock system just downstream are unsteady and fluctuate near the abrupt stall conditions.

However, the addition of the snag was not the only geometric difference between the F/A-18E and the F/A-18C that significantly influenced the flow. Green computed angles of attack at which abrupt stall was predicted to occur for the baseline F/A-18C wing and then repeated these same computations for the F/A-18C wing modified to incorporate the various geometric differences between the F/A-18C wing and the F/A-18E wing. He examined individually, and in selected combinations, the effects of adding the snag, reducing the local chord of the leading-edge flap, reducing leading-edge radius, increasing the thickness of the wing, and removing camber and twist. As reported by Green,[14] the addition of the leading-edge snag and the reduction of the local leading-edge flap chord associated with the F/A-18E leading edge were the primary factors influencing the increased sensitivity of the pre-production F/A-18E to abrupt stall. In addition, for the application of a snag as implemented by the F/A-18E, the lateral location of the minimal leading-edge flap local chord is just inboard of the snag and is at the position where the flow about the flap is hardest to manage because of the snag upwash. Figure 7 summarizes the impact of adding the snag to the baseline F/A-18C and of adding both the snag and the reduced leading-edge flap chord. The resulting increases in the separated flow with the addition of each of the geometric changes are dramatic.

Insights into design were also gained by conducting CFD computations on three other configurations—the AV-8B, the F/A-18C, and the F-16C.[8,9] In the analysis by Parikh,[8] it is clear that there were significant differences in sectional lift distribution as a function of angle of attack between the pre-production F/A-18E and the F-16C, which is known not to exhibit wing drop (see figure 8). The sectional lift distribution of the pre-production F/A-18E exhibits a lot of nonlinearities while the sectional lift of the F-16C, while not shown due to public release difficulties, was extremely well-ordered and linear in appearance. Examining sectional lift distributions across the wing through the stall process using CFD codes can give a quick glance at how abrupt, or smooth, the stall process is and may form the basis for a design metric.

Impact of Results

1. New guidelines are provided for the density of experimental and CFD data required to describe the aircraft behavior through the potential abrupt stall region. For example, it is not feasible to test with 2° increments in angle of attack and detect the abrupt character of the wing stall. Smaller increments, on the order of 0.5°, are needed in the wing stall angle-of-attack range.

2. The findings involving the unsteady character of the experimental pressures as well as the unsteady nature of the COBALT DES solutions may have important implications. The presence of these shock oscillations may provide a trigger for the wing-drop motion. It is not clear yet, however, if determining time histories is required to (1) predict lateral motions or (2) understand the abrupt stall process.

3. Design insights are provided by morphing work by Green[14] as well as other computational studies.[8,9,17]

4. The work by Green provides a methodology to obtain the background information to make trades between the transonic maneuver capability and other mission requirements. With his approach, it is possible to quantitatively assess the impact on transonic maneuver limits of geometric modifications such as adding snags, reducing flap chord length, thickening wings, and removing camber and twist.

Developing Methods And Approaches

State of the Art

Prior to and during the F/A-18E resolution effort, transonic wind tunnel test data lacked credibility with regard to predicting wing drop. This lack of credibility was due to the fact that several modifications to the subscale models that appeared to show significant improvement during the tunnel testing proved to be disappointing when applied to the aircraft and evaluated by flight test. Computational tools had not been fully validated against wind tunnel or flight data and also lacked metrics. In addition, the mathematical simulation of the F/A-18E did not have the capability to accurately resolve relatively abrupt changes in aerodynamic properties. In general, the methods and approaches were not in place to assist the wing-drop resolution effort in a timely and reliable manner. Consequently, flight test, with its costs, limitations, and "cut and try" approach, was considered the definitive tool with which to evaluate modifications.

AWS Efforts

Significant effort was expended to thoroughly explore candidate figures of merit for both wind-tunnel experiments and CFD. The most desirable means of predicting uncommanded lateral activity would be during the usual static, or conventional, testing early in the development process. Consequently, much of the effort for experimental figures of merit involved examining the results of static wind-tunnel testing. All wind-tunnel entries performed by the AWS Program were scrutinized on this basis.

However, it became clear from historical data[19,20] and from data being collected during the AWS experiments that static figures of merit may not have sufficient reliability to confidently predict activity before going to flight test. Consequently, an effort began to adapt an existing dynamic testing technique allowing the model to be free-to-roll (FTR) about its body axis to assess dynamic stability. The FTR technique had been used for low-speed evaluations[21,22] but

had not been used transonically. A slightly different approach was used for a new transonic FTR rig,[11] which was to mount the rotating fixture in the support structure downstream of the model sting. This was in contrast to the usual low-speed approach, which replaced the model balance with a fixture within the model that permitted body-axis rotation. This new approach permitted testing with a typical metal model built for performance testing, its model balance, and its model sting. In addition, the approach permitted both static, or conventional, testing when the FTR feature was locked out with a bar and then immediate FTR evaluation by removing the locking bar if anything suspect was seen in the static testing results. As a result of this design, FTR testing could be concurrent with static testing and there would be no need to build a special model or to schedule a dedicated wind-tunnel entry at a later date.[11]

The other major thrust of this specific research topic area within the AWS Program was in the area of flight dynamics and simulation, see figure 9. As mentioned, the initial mathematical simulation of the F/A-18E was not designed to model abrupt nonlinear changes or asymmetries in aerodynamic coefficients. Furthermore, it was not understood what variables, or combination of variables, had to be modified to adequately simulate the wing-drop events seen in flight. Once this was accomplished, an additional objective of this effort was to determine if pilots in a fixed-based simulator could get enough visual cues to interpret the aerodynamic response as a wing drop.[15,18]

Accomplishments

The effort expended to develop static figures of merit arrived at the same conclusion as the efforts of Boeing during the resolution effort with the pre-production F/A-18E—there is not one all-encompassing static figure of merit that is reliable for general configurations.[10]

On the other hand, the results with the FTR rig met or exceeded expectations.[12,16] As will be detailed under the next major topic, the FTR technique is considered a robust national asset and is recommended to resolve any questions identified during static testing.

Simulation modifications were also successful in all objectives.[15] First, modifications to the simulation were developed which permitted the modeling of abrupt nonlinear events, such as wing drop. Second, it was found that the key input variables that are required to adequately model a wing drop are asymmetric rolling moments at zero sideslip and reductions in roll damping. Both of these variables can be measured during either static testing or determined by applying parameter identification techniques to the FTR data. Third, it was also demonstrated that fixed-base simulators could replicate a wing drop realistically, based on pilot evaluations from pilots familiar with wing drop in flight.

Impact of Results

1. Static, or conventional, wind-tunnel testing is not sufficient to reliably predict angles of attack at which uncommanded transonic lateral activity will occur in flight.

2. Testing with a FTR rig will provide a robust indication of possible uncommanded lateral motions in flight. This capability should be used to evaluate all new configurations that maneuver at transonic conditions with highly separated wing flows.

3. Piloted simulation, when modified as developed during the AWS Program, can replicate wing drop in a realistic manner. When the simulation data bases are provided with values of roll asymmetries at zero sideslip and values of roll damping from FTR testing, simulation should be capable of evaluating the impact of those nonlinearities on mission performance before going to flight test.

Assessment

State of the Art

Since much of the early AWS research involved the pre-production F/A-18E/F configuration, it was recognized that all of the derived AWS figures of merit, methods, and approaches would have to be assessed and validated for other configurations as well. Specifically, the goal was undertaken to validate these AWS efforts by testing another aircraft that exhibits wing drop, the AV-8B (near the extremes of its flight envelope), and by testing two other aircraft that do not exhibit wing drop in

flight, the F/A-18C and the F-16C. If any of the figures of merit or methods from the AWS Program were going to have credibility, these figures of merit and methods would have to be effective for another configuration susceptible to wing drop and for those that are not.

AWS Efforts

The approach taken by the AWS Program was to evaluate all four aircraft by (1) performing CFD calculations at conditions representative of the FTR wind-tunnel test program and (2) conducting both static, or conventional, testing and FTR testing. As previously stated, the two aircraft that were susceptible to wing drop were the pre-production F/A-18E and the AV-8B. Since these two configurations have very different wing characteristics, see figure 10, there was reason to suspect that there could be differences in the flow mechanisms of wing drop and wing rock for these two aircraft. The two aircraft configurations that did not exhibit drop in flight, the F/A-18C and the F-16C, were considered a control group. The four models representing these aircraft are shown in figure 11 as they were tested in the Langley 16-ft Transonic Tunnel.

The databases developed by CFD and the wind tunnel were then utilized for a number of critical analyses. First, both sets of data were used to evaluate the accuracy of candidate static figures of merit.[8,9,10,16,17] Second, the experimental FTR data were evaluated by comparing to flight data for each of the configurations.[12,16] Third, the wind tunnel data were also used to calibrate the static predictions of forces and moment for the CFD results. [8,9] The first two of these analyses were critical in order to establish a risk reduction approach for future aircraft.

Accomplishments

The assessment program was highly successful in reaching its objectives. With regard to static figures of merit, it is reported by Lamar[10] that they are not robust predictors of lateral activity. For example, if nonlinearities are present in the lift-curve slope, then lateral activity, such as wing drop, may occur at that angle of attack or at a higher angle of attack or not at all.[10] Of course, part of the difficulty with the static figures of merit is in determining thresholds magnitudes for "significant" slope changes in the respective parameters. The problem is that such thresholds are not obvious from the present work and may actually vary from configuration to configuration.

The agreement between the FTR predictions of lateral activity and what is known from flight test experience is very good.[12,16] While some development of metrics for this technique has been necessary, it appears that an averaged rate metric[12] appears to be most indicative of lateral activity. This metric is similar to the rate parameter conceived for the flight figure of merit developed by Roesch and Randall.[13]

With the FTR technique established as a feasible testing technique at transonic speeds, it is now possible to define a procedure for predicting if a future vehicle will experience uncommanded lateral motions, such as wing drop, before going to flight. The procedure is outlined in figure 12. The steps are to first conduct static-wind tunnel experiments. If alerts are raised in this first stage—such as lift-curve breaks, asymmetries in rolling moment, or peaks in rolling-moment unsteadiness with angle of attack—then it is necessary to evaluate the configuration with the free-to-roll technique. (NOTE: if the vehicle has to maneuver through wing stall, then FTR testing is strongly recommended.) After FTR data are obtained and if issues remain, then assessments with piloted simulation are in order. The purpose of the piloted simulation would be to determine if what was seen in the tunnel would significantly impact the vehicle mission. If not, the potential problem can be dismissed. If, however, there is an impact on mission performance, then two typical approaches to explore are to (a) redefine the flap schedule to try to work around the conditions at which the lateral activity is predicted to occur or (2) attempt to upgrade the lateral control system with either faster sensors or faster actuators. If these efforts fail, then an aerodynamic configuration change will have to be explored.

The computational results were generally representative of the experimental data obtained for the F/A-18E, the F/A-18C, and the F-16C. [8,9] An exception to this was the calculations for the

AV-8B.[9] The CFD solutions predicted wing stall several degrees below that measured in the wind tunnel. This discrepancy is believed, at least in part, to be caused by differences between the full aircraft geometry and the geometry modeled in the CFD calculations. While the AV-8B flies with one vortilon (similar to a leading-edge fence) and 11 vortex generators on each wing panel to delay wing panel stall, these geometric features were not represented in the CFD grid. In hindsight, it would seem logical that if those devices were tested and placed on the aircraft, they were there for an important reason. Calculations are planned that will determine if the absence of the vortilons and vortex generators on the CFD wing panels were responsible for the mismatch in force and moment predictions between the wind tunnel and CFD.

Impact of Results

1. The most significant impact from the aircraft configuration assessment was the clarification of limitations involved with the static figures of merit and the success of the FTR technique and its metrics. Within the limitations of having only evaluated four aircraft, the FTR technique appears to be a robust predictor of uncommanded lateral motions in flight.

2. A recommended procedure to determine if a future flight vehicle has the potential for lateral motions, before going to flight, has been defined.

LESSONS LEARNED

This section will group the lessons learned into the three categories of wind tunnel, computations, and simulation.

Wind Tunnel

1. FTR testing is a necessity for insuring a reliable prediction of what will happen in flight.[12] Using available metal transonic models that are not dynamically scaled is still useful for predicting lateral activity. Having the ability to remotely trim out any roll offsets for the models would be helpful. Conducting continuous pitch sweeps, pitch-pause runs, and phi-offset runs all result in unique information because of the importance of initial conditions. (Conducting complementary static tests assessing static rolling moments as a function of wing bank angle is extremely informative for the interpretation of the FTR results. Hysteresis in rolling moment with sideslip was found to be significant during some of these tests so testing must include runs to quantify this effect.)

2. Within the current assessment of four aircraft, it is clear that static FOM's appear to be inadequate for predicting uncommanded lateral motions in flight.[10] On the other hand, FTR testing and evaluation appears to be robust. However, as additional configurations are tested, it is expected that more may be learned in terms of the interpretation of the FTR results.

3. During conventional, static wind-tunnel testing, it is necessary to be conscious of warning signs, such as severe model dynamics, that are a signal that the flow may be changing topologies. If flow topologies are changing abruptly, lateral activity is a possibility. Other key indicators are asymmetries in rolling moment, peaks in rolling moment unsteadiness, and lift-curve nonlinearities.

4. During static and dynamic testing, it is necessary to increase the density of data acquired near the wing stall or topology change. It is suggested that the increment in angle of attack be 0.5°, or less. If increments are larger than this value, then the abrupt changes in lift slope or rolling moment may be missed.[4]

5. Because of the inherent unsteadiness associated with abrupt wing stall, it is important to take repeat data for critical conditions or angle-of-attack sweeps. As found by McMillin,[4] differences in the onset of lift-curve breaks and in the magnitudes and trends of rolling moment asymmetries can occur over the duration of a wind-tunnel entry. Contributing to the scatter in the data are any changes to the critical leading-edge region of the wing due to repair of boundary-layer transition cylinders or grit, reinstallation of leading-edge flap sets, or other similar changes.

6. The most cost-effective instrumentation addition for an abrupt wing stall wind-tunnel test is to add wing-root-bending gauges on both wing panels.[10]

7. The Pressure-Sensitive-Paint method

results in useful flow images but is very time intensive.[4]

8. When instrumenting a model for abrupt stall investigations, instrument both the left and right wing panels with similar instrumentation. During the unsteady pressure studies that the AWS program conducted, only one wing panel used the unsteady pressure transducers. Having even a subset of the unsteady transducers on the other wing panel would have enabled better analysis.[6]

9. Any instrumentation trenching on wind tunnel models should be placed on the lower wing surfaces. Different thermal conductivities associated with the fill material degrade Pressure-Sensitive-Paint images.[4]

10. Figures of merit must be applied to several aircraft configurations before being considered reliable and validated.

Computations

1. Unsteady CFD calculations for the F/A-18E showed that Detached-Eddy Simulation (DES) provides a credible means of calculating the unsteady effects associated with abrupt wing stall. The simulations were roughly 10 times more expensive than steady calculations. While expensive, they are possible today, and could become more routine as processor speeds increase. An efficient way to employ unsteady calculations would be to first conduct steady calculations in small increments to identify the potential AWS angles and then narrowly focus DES calculations on these angles. DES calculations on a full aircraft showed that shock oscillations on each wing panel can be out of phase and thereby provide the initial impetus for an AWS event.[7]

2. While greater flow physics are captured by the unsteady DES calculations, the static calculations still yield sufficient information to predict the abrupt wing stall region.[17]

3. The need for fine increments in angle of attack holds true for computations as it does for wind-tunnel testing. Increments at least as fine as 0.5° are needed to appropriately describe the stall break.[14]

4. Turbulence models have an impact, as does grid density. Large changes in configuration should be accompanied by some attempt at code validation with wind-tunnel force and moment information and as well as either oil-flow images or Pressure-Sensitive Paint (PSP) images, if available.

5. Frequency of shock oscillations and the magnitude of rolling-moment asymmetry were shown, for the F/A-18E, to be independent of whether the calculation was done on a half-plane grid or on a grid with both left and right wing panels.[7]

6. To describe the stall progression process, it is necessary to employ higher-order CFD codes with a Navier-Stokes level of technology.[8]

7. If the aircraft under consideration will have fences or vortex generators, then those devices must be modeled for CFD.[9]

Simulation

1. Asymmetries in the wind tunnel data cannot be ignored when building the aerodynamic database for the mathematic simulation of a high-performance aircraft at transonic speeds. Specifically, rolling-moment asymmetries at zero values of sideslip, C_{l0}, are a good example of what is typically, but arbitrarily, changed to zero before being placed in the simulation. While it is possible to have C_{l0} offsets due to tunnel swirl or model asymmetries, these would be expected to be relatively constant over the angle-of-attack range and should be eliminated. The asymmetries that are important to retain for the simulation description are those that depend sharply on angle of attack and are resulting from asymmetric wing stall. It is also possible to estimate values of roll damping from the FTR testing. These data are also essential to proper modeling of a configuration in simulation.[15]

2. Increments in angle of attack are an issue for simulation as well as the tunnel and CFD. Here the need is for sufficiently fine angle of attack increments in the simulation so that a nonlinear change over a degree or two can be modeled. This is necessary to capture abrupt discontinuities in rolling moment at zero values

of sideslip and roll damping as the aircraft passes through abrupt stall.[15]

3. Having a flight figure of merit, such as that of Roesch and Randall,[13] is an absolute necessity for being able to evaluate the potential impacts of the nonlinearities seen during the experiment.

RESEARCH OPPORTUNITIES

With the AWS Program nearing its expected conclusion at the end of Fiscal Year 2003, it is timely to suggest follow-up research in two areas, based on current experiences. The first topic involves a more fundamental examination of design guidelines than was practical during the AWS Program. The second topic is to actively pursue applying state-of-the-art CFD to stability and control problems.

Developing Generic Design Guidelines

The first recommendation is for a more fundamental assessment of design guidelines than was possible within the AWS Program. While the AWS program has delivered a number of insights for design guidelines—impact of adding snags, reducing leading-edge flap chords, removing twist and camber, reducing leading-edge radius, etc.—it was not possible to develop general design guidelines that direct how to configure a new aircraft that is resistant to uncommanded lateral motions. (The AWS methodology can currently only evaluate an existing configuration. It cannot guarantee that a new configuration is problem free without experimental or computational assessments.) Thus, there is a need for a more generic look at establishing design guidelines.

Because of the accomplishments of the AWS Program, the groundwork for a more generic effort has been established. Because of the existence of FTR figures of merit, it is not necessary to conduct research on aircraft configurations that already have flight data available. Consequently, it is now possible to envision a more fundamental investigation in which it will be possible to test with generic shapes unrelated to flight vehicles. Fabricating simple, more generic, shapes would be less expensive. Computationally, simpler shapes would require fewer computational resources and, subsequently, would facilitate varying geometric parameters. The goal of the study would be to determine the design parameters that drive the abruptness of the stall progression for a range of configuration variables. For example, is the abruptness driven by the flatness of the pressure distribution or the sectional lift properties? Parameters to be examined should include: (a) Mach numbers from low-speed to supersonic, (b) role of airfoil sections, (c) role of sweep and three-dimensional effects, and (d) role of Reynolds number effects.

Role for CFD In Stability and Control Issues

Whereas the aircraft performance community has successfully embraced advanced CFD codes as valuable tools which complement experimental methods, the stability and control community has not had the same opportunity. There are several reasons for this. For example, the computer resources required have often been prohibitive because (1) critical problems in stability and control involve massively separated flows, which require grids with sufficient resolution to resolve shear layers in the separated flow regions, (2) the full aircraft must be gridded, in contrast to half-plane calculations for performance, because of potential asymmetries due to differential control surface settings or due to sideslip, and (3) there can be a significant degree of flow unsteadiness. With current computers and codes as reported in the AWS papers,[5,8,9,14,17] the time has arrived for serious attempts to bring state-of-the-art viscous codes into the stability and control arena. The application of CFD to stability and control can, with its flow diagnostic abilities, help the wind-tunnel engineers understand the flow physics occurring during the model testing, can reduce the scope of wind-tunnel testing required, and can accelerate the process of improving a design.

A first step in this direction might be to apply the CFD tools used in the AWS studies to the task of estimating transonic damping derivatives. In the early days of aviation, two-dimensional strip theory was used to estimate this parameter with good success for the low-speed aircraft of the day. However, for the transonic, three-dimensional separated flow

phenomena of abrupt wing stall, this more sophisticated approach is needed.

SUMMARY

At the beginning of the AWS Program, the F/A-18E/F Program had just resolved an unexpected wing drop problem with the pre-production F/A-18E by the modification of its leading-edge flap schedule and the addition of the porous wing fold fairing door. This problem was rectified through "cut and try" experiments and a critical discovery made in flight test by a creative test pilot. The usefulness of transonic wind-tunnel testing and conducting viscous Computational Fluid Dynamics (CFD) solutions was limited during the pre-production F/A-18E resolution process. Figures of merit, or metrics, had not been established for the conventional wind tunnel testing and several configuration modifications that appeared to be promising, based on subscale wind tunnel results, proved to be disappointing in flight test. For CFD, the challenges of developing figures of merit, code calibration and validation, and lengthy times required to produce solutions combined to limit the direct contribution of CFD to the solution. While many aircraft development programs had experienced the physical phenomena of wing drop and wing rock in the past, a national program to advance the state of the art of prediction and mitigation of the problem had never been undertaken.

The uniqueness of the AWS Program is that it was a coordinated, and focused technical program that brought current tools, methods, and facilities to the problem of uncommanded lateral motions, such as wing drop or wing rock, at transonic conditions. The scope and activities were extremely broad, including detailed transonic wind-tunnel testing for flow diagnostics and understanding, a broad-based CFD effort involving the application and assessment of three major codes, and pioneering simulation research to develop and validate mathematical modeling of aerodynamic phenomena and figures of merit from a pilot's perspective. The primary goal of the AWS effort was to provide the flow understanding, tools, and figures of merit so that the participants in future aircraft programs could reliably predict the vehicle's propensity to exhibit uncommanded lateral motions and to provide solutions to the potential problem prior to flight test.

The AWS Program initially studied the transonic flow about the F/A-18E with a variety of computations and with a variety of transonic wind-tunnel instrumentation approaches. In addition to exhaustive studies of the flow characteristics of the F/A-18E, the AWS Program also utilized three other aircraft configurations to determine the validity of testing and CFD results in light of actual flight experience. These three aircraft included the AV-8B, an aircraft that was known to exhibit wing drop at the extremes of its flight envelope, and the F/A-18C and the F-16C, aircraft that are both known not to exhibit wing drop. Having a total of four aircraft to evaluate proved to be critical to the success of the AWS Program. Some figures of merit that looked promising for the pre-production F/A-18E did not function as well for the other aircraft.

Design insights were obtained by (1) analyses on these four aircraft and (2) conducting a morphing exercise in which the wing of the baseline F/A-18C, a non-dropper, was modified to incorporate the pertinent wing differences between the F/A-18E and the F/A-18C. The critical geometric differences between the F/A-18E and the F/A-18C were determined to be (1) the presence of the leading-edge snag and (2) the reduced leading-edge flap chord. These two differences appear to account for most of the increased sensitivity of the pre-production F/A-18E to wing drop.

With the progress that the AWS Program has demonstrated, it is now possible to experimentally assess the propensity of a vehicle to have uncommanded lateral activity as soon as a wind tunnel model can be tested. A major contribution of the AWS Program is the development of a transonic Free-to-Roll (FTR) technique, which allows the wind-tunnel model to freely rotate about its body axis as it reacts to asymmetric wing panel stall or to the presence or absence of roll damping. Figures of merit for conventional, or static, testing have been demonstrated to be unreliable in predicting uncommanded lateral motions, especially when evaluated over a variety of aircraft configurations. Other AWS progress occurred in

the area of simulation. A procedure was demonstrated that permits modeling, by fixed-based piloted simulation, of potential mission impacts of the AWS activity measured in wind tunnel testing before going to flight. This can alert a program several years in advance of when the program would have historically detected such a problem in test flight.

With the current progress from the AWS Program, the AWS methodology can, given a defined configuration, assess its propensity to have uncommanded lateral motions. However, the results of the current program cannot guide a designer on how to initially design a configuration without the possibility of uncommanded lateral motions. Consequently, follow-up research recommendations are made to address the need for general design guidelines. In addition, the time has come to more aggressively apply CFD codes to the stability and control arena. In particular, there is an urgent need to predict roll damping. While that information can be extracted from the FTR technique or from forced-ocscillation testing, there are operational limitations.

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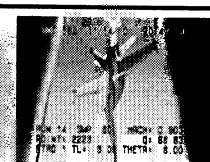
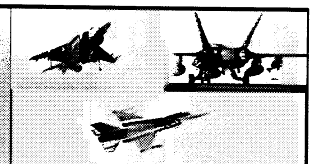
FIGURES

			
Analyze Legacy Data for F/A-18E and Other A/C	**Flow Understanding**	**Develop Methods and Approaches To Predict Abrupt Stall**	**Assess Other Configurations**

• Wind tunnel data
  • Force & moment
  • Oil flows
• Legacy CFD and grids
• Flight data
• Historical review of transonic AWS experiences with other A/C
	• Wind tunnel diagnostics:
	  • Pressures
	  • PSP
	  • WRBM
	  • Unsteady
	• CFD
	  • Structured
	  • Unstructured
	  • Unsteady
	• Impact of wing differences
		• Transonic Free-to-Roll method
		• Figures of Merit (FOMs) for
		  • Wind tunnel
		  • CFD
		• Simulation improvements and validation
			• One with activity (AV-8B)
			• Two without activity (F/A-18C, F-16C)
			• Calibrate FOMs for all configs
			• Correlate with flight
			• Define recommended risk reduction approach

Figure 1. Major research areas for the AWS Program.

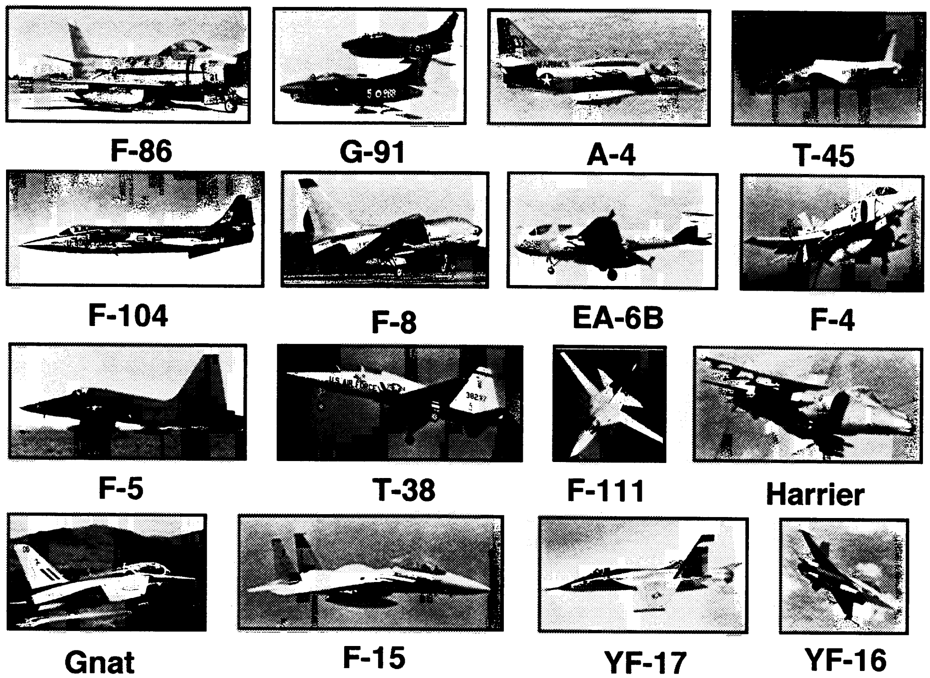


Figure 2. Examples of high performance aircraft that have had to deal with uncommanded lateral motions, see Chambers.[3]

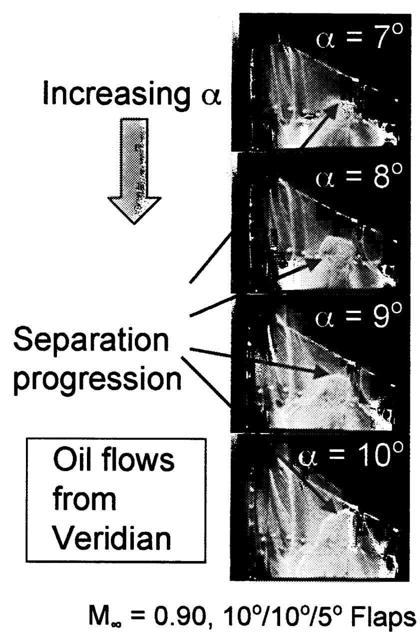
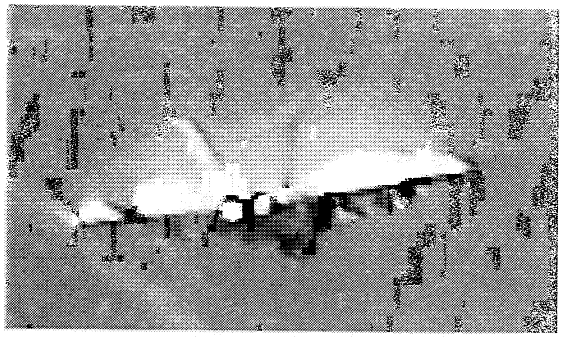
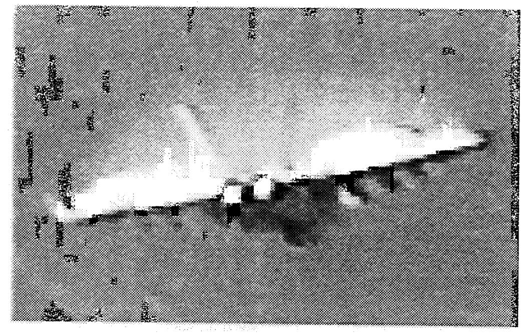


Figure 3. Progress of flow separation with angle of attack from legacy oil-flow images taken in the Veridian 8-ft transonic tunnel.

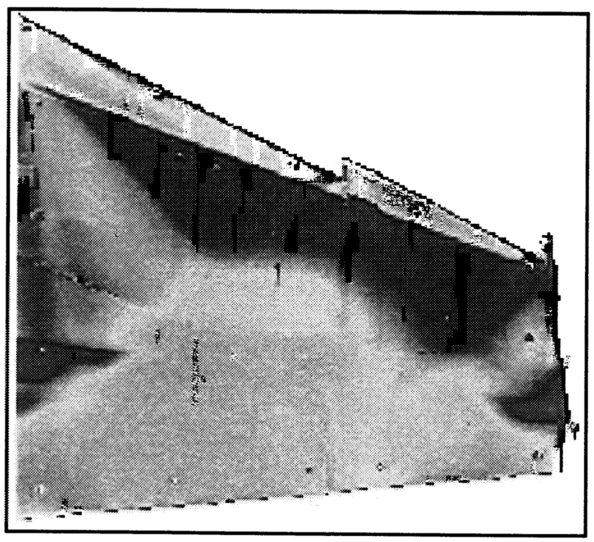


(a) Note gap in condensation on left wing

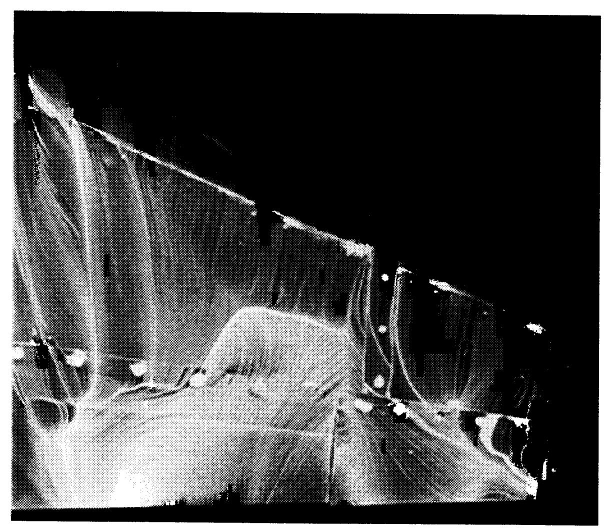


(b) Fuller condensation pattern moment later

Figure 4. Naturally occurring condensation over the F/A-18E wing was unsteady near wing drop angles of attack.



(a) PSP image



(b) Oil flow image

Figure 5. PSP image from Langley 16-ft Transonic Tunnel correlates well with Veridian oil flow. 0.08-scale F/A-18E model, Mach = 0.90, $\alpha = 8°$.

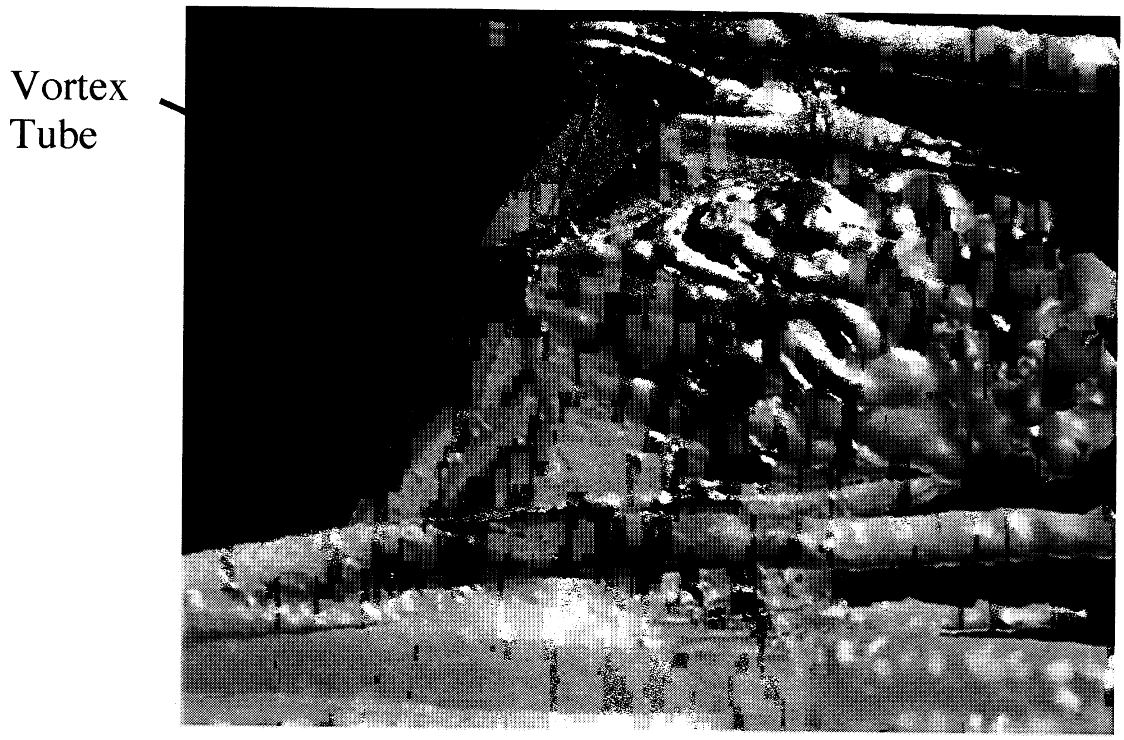
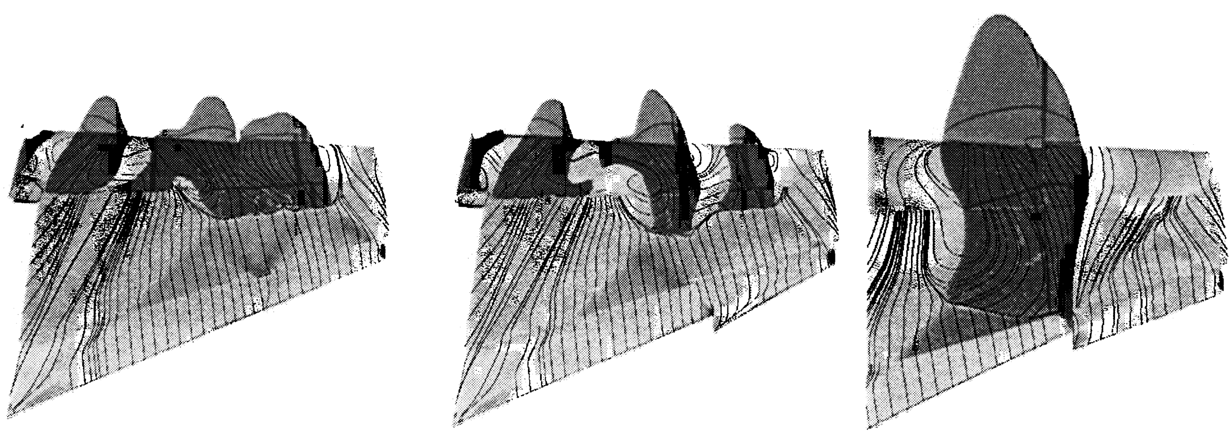


Figure 6. This plot highlights the vorticity generated by the flow separation. Note tube of vorticity emanating just inboard of the leading-edge snag. $M_\infty = 0.90$, $\alpha = 9.0°$



(a) Baseline

(b) Baseline + snag

(c) Baseline + snag + reduced chord leading-edge flap

Figure 7. Results of Green[14] showing impact of geometric modifications to F/A-18C wing. $M_\infty = 0.90$, $\alpha = 9°$.

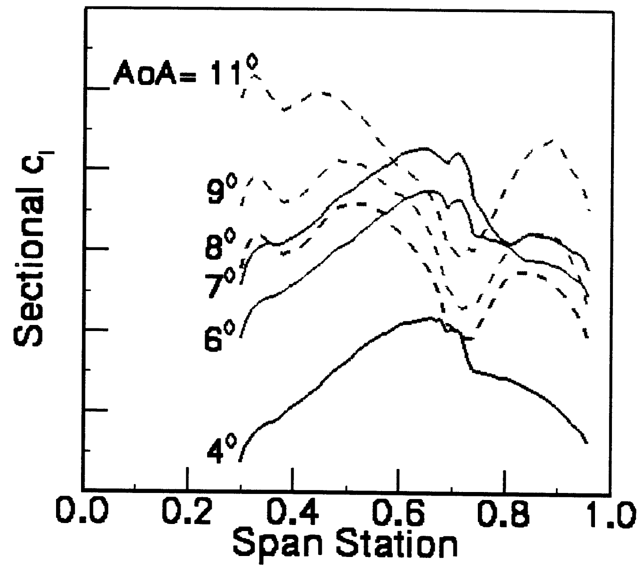
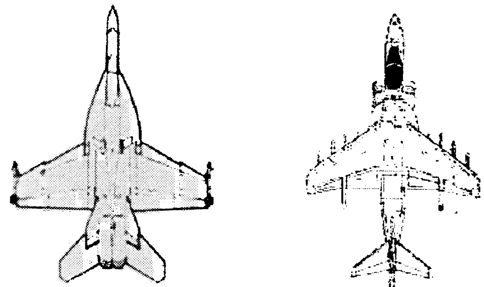


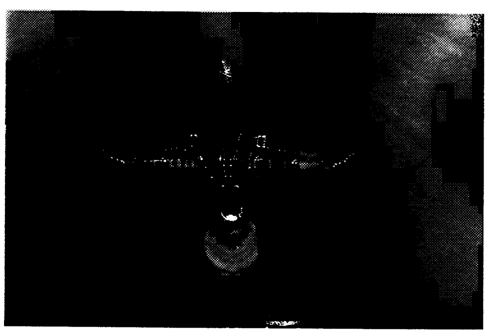
Figure 8. Sectional lift distributions for the pre-production F/A-18E at $M_\infty = 0.80$.

Figure 9. Piloted simulation demonstrated to reproduce wing drop.

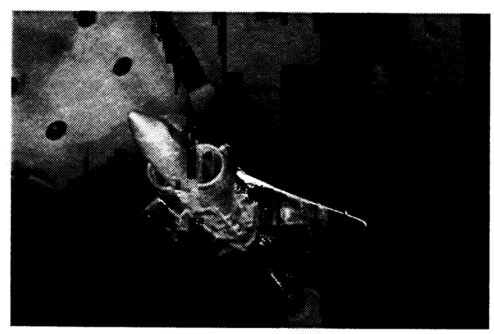


Parameter	F/A-18E/F	AV-8B
Aspect Ratio	3.5	4.0
Leading Edge Sweep	29.4°	36°
Airfoil	Uncambered	Supercritical
Leading Edge Radius	Essentially Sharp	Blunt
Thickness Ratio	6.2% to 4.3%	10.5% ave
Twist	None	0° to 8°
Dihedral	-3.4°	-10.3°
Leading Edge Snag	Yes	No
Leading Edge Flap	Yes	No
Trailing Edge Flap	Yes	Yes
ALEX/ARef	15%	4%

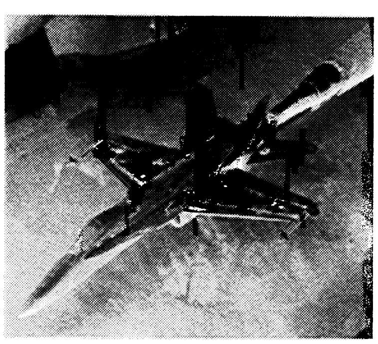
Figure 10. Wing drop occurs for wings with significant differences.



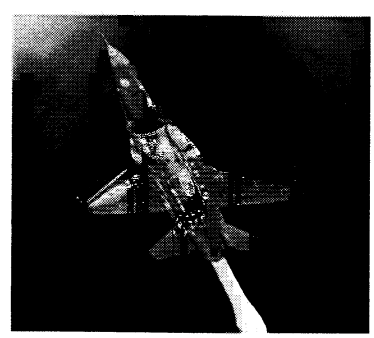
(a) Pre-production F/A-18E



(b) AV-8B



(c) F/A-18C



(d) F-16C

Figure 11. Four aircraft evaluated by both static and FTR testing in the Langley 16-ft TT.

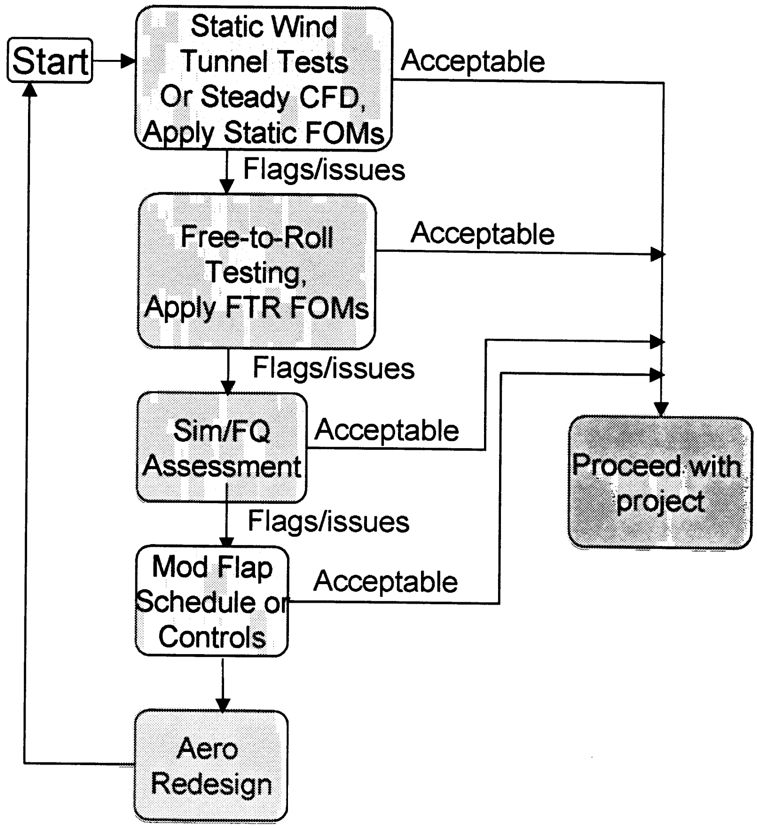


Figure 12. Proposed risk reduction process for future vehicle programs.